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(54) **REMOVABLE MODULAR ANTENNA ASSEMBLY FOR DOWNHOLE APPLICATIONS**

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(52) **U.S. Cl.**
CPC ***E21B 47/122*** (2013.01); ***E21B 17/028*** (2013.01)

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CPC E21B 47/12; E21B 47/122; E21B 17/028; E21B 43/10; E21B 43/103; E21B 43/106; H01Q 1/04; G01V 3/30
See application file for complete search history.

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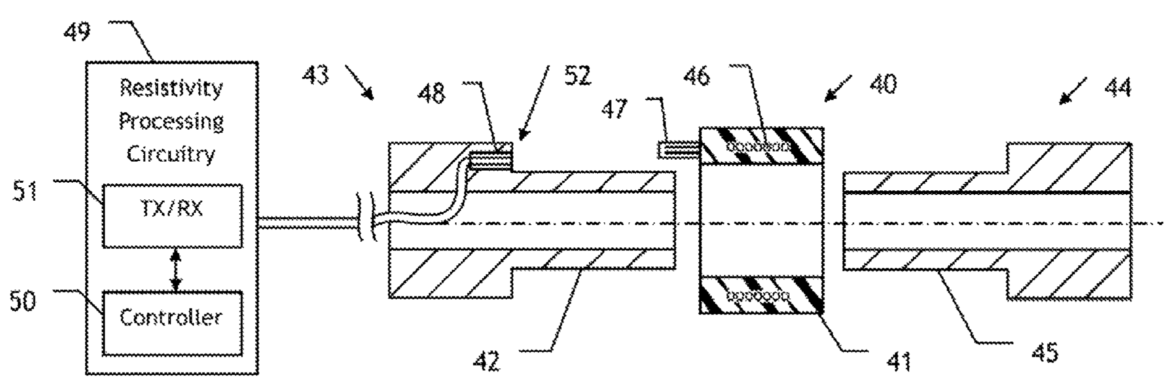
(57) **ABSTRACT**

A wellbore apparatus may include first and second tubular members joined together in end-to-end relation, the first tubular member having a reduced outer diameter end portion. The wellbore apparatus may further include a removable modular antenna assembly comprising a cylindrical dielectric housing removably positioned on the reduced outer diameter end portion of the first tubular member, at least one antenna coil carried by the cylindrical dielectric housing, and a first electrical connector coupled to the at least one antenna coil. The wellbore apparatus may also include resistivity processing circuitry coupled to the first electrical connector to determine an electrical resistivity of a wellbore based upon the at least one antenna coil.

20 Claims, 4 Drawing Sheets



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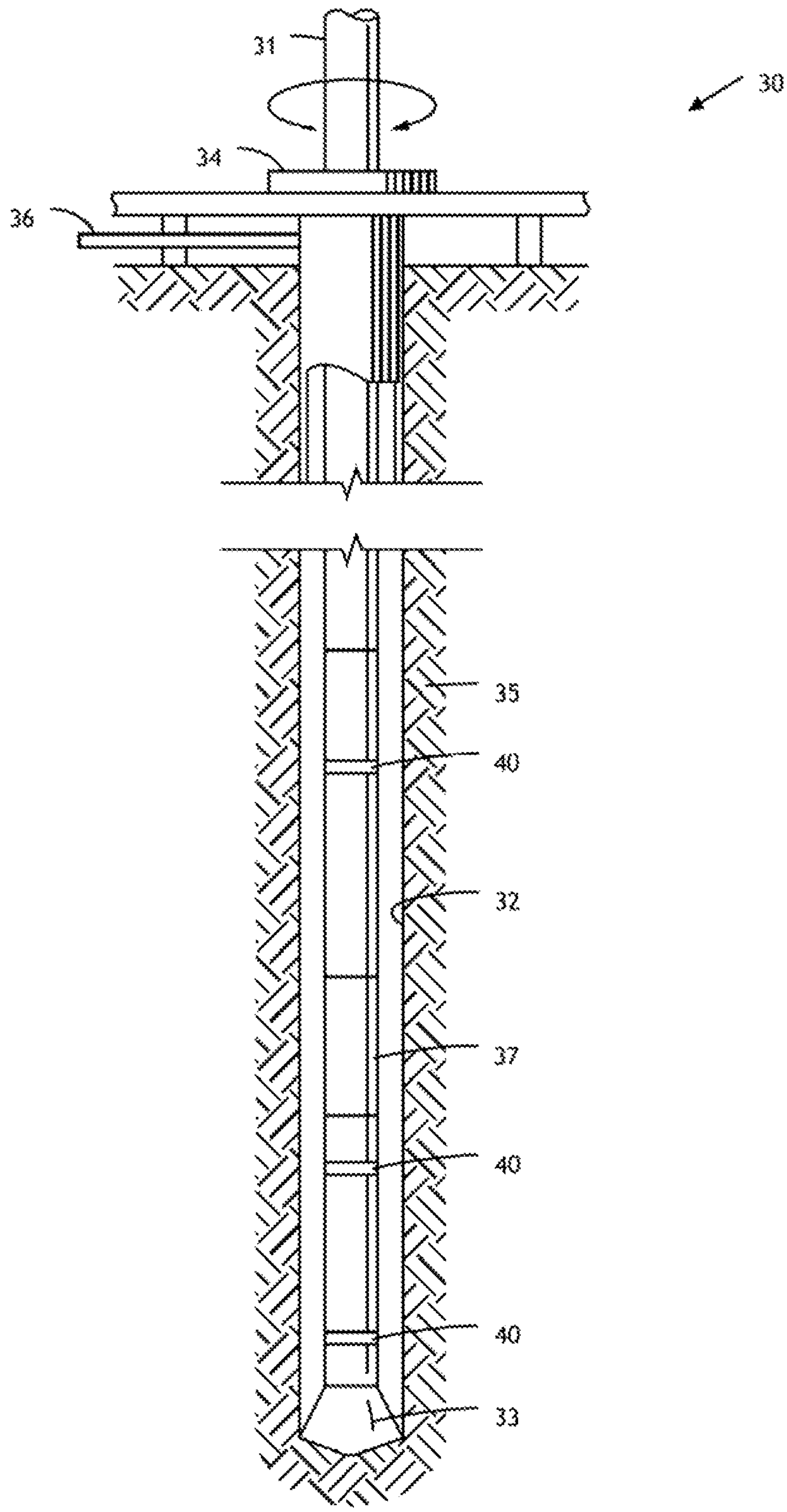

FIG. 1

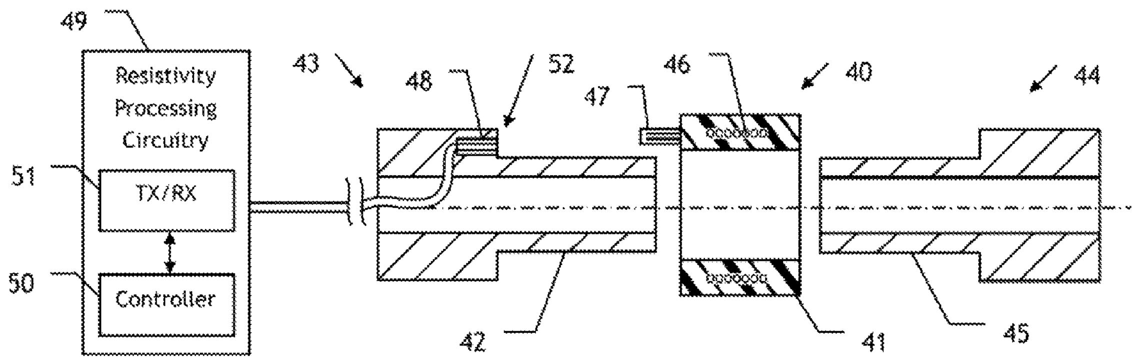

FIG. 2

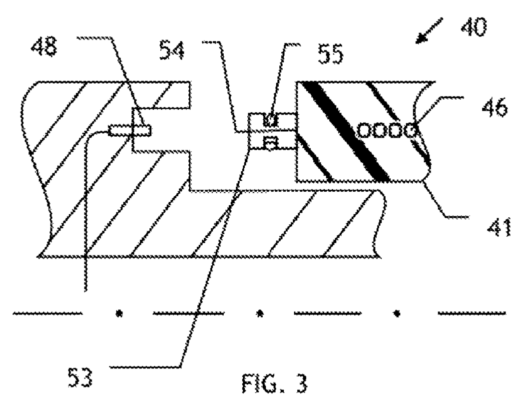

FIG. 3

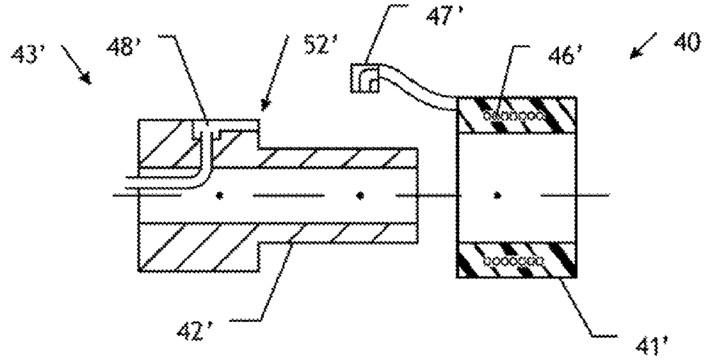

FIG. 4

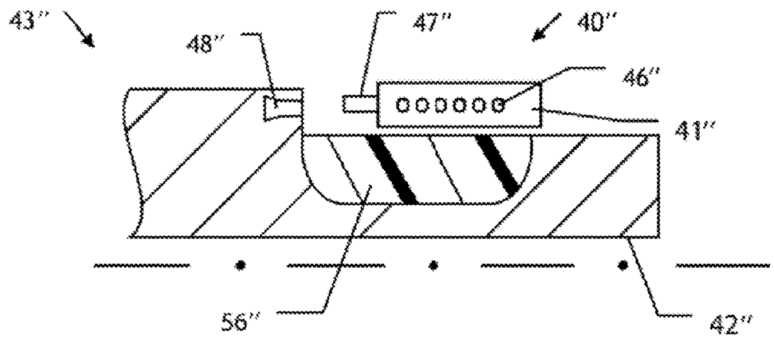

FIG. 5

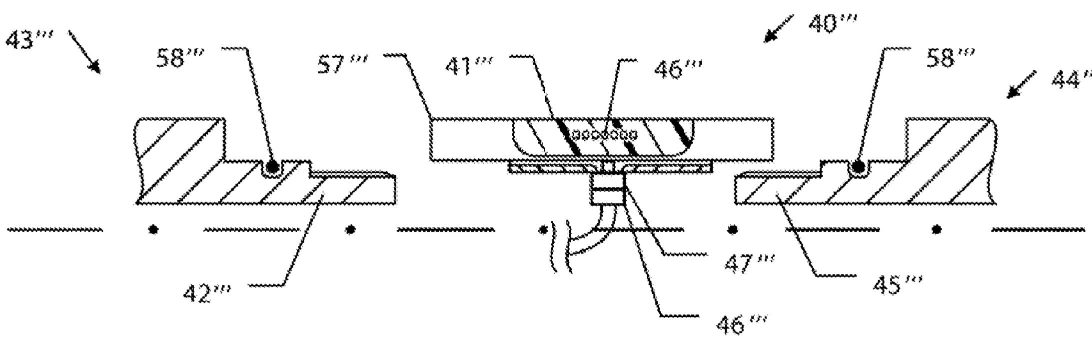

FIG. 6

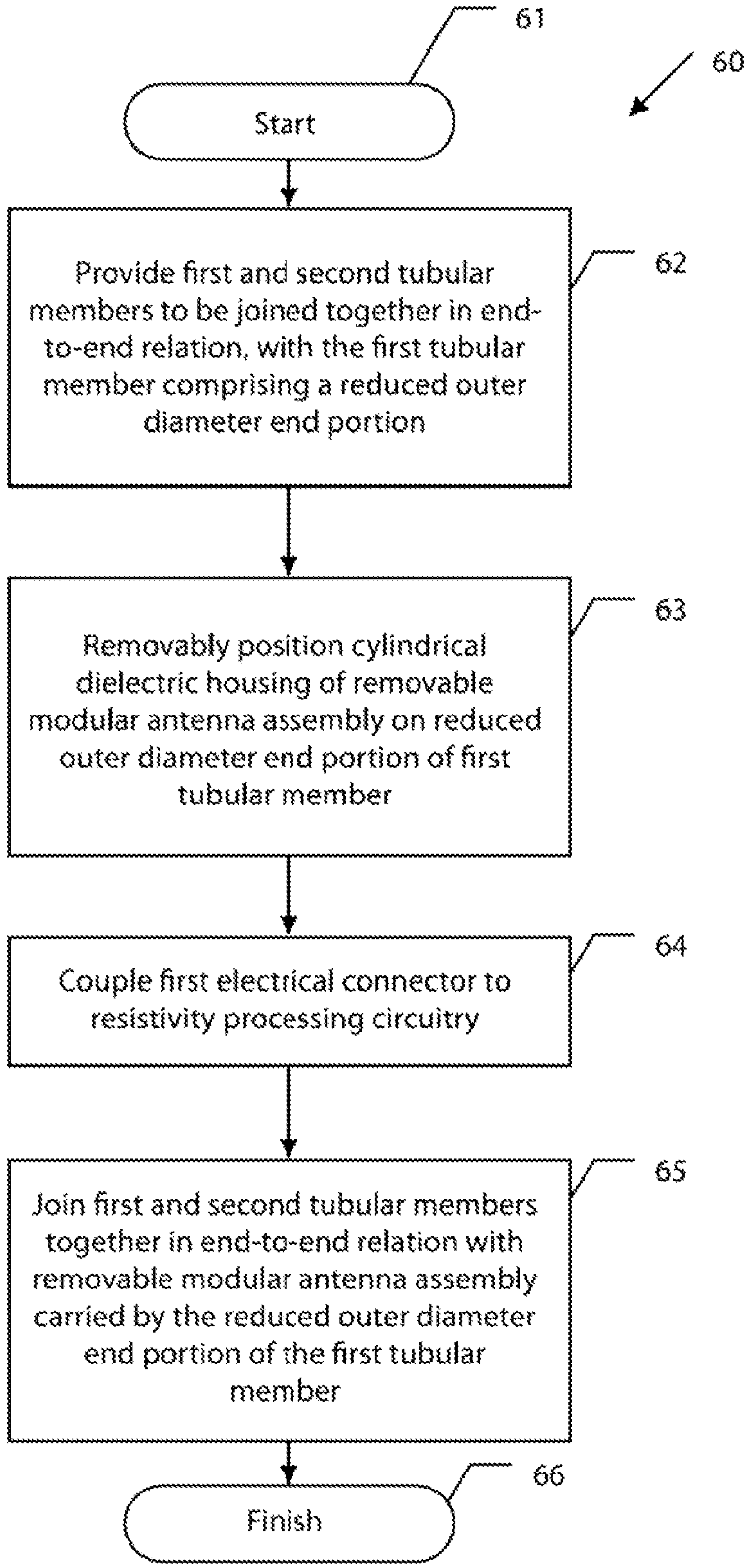
61
60
Start
Provide first and second tubular members to be joined together in end-to-end relation, with the first tubular member comprising a reduced outer diameter end portion
62
Removably position cylindrical dielectric housing of removable modular antenna assembly on reduced outer diameter end portion of first tubular member
63
Couple first electrical connector to resistivity processing circuitry
64
Join first and second tubular members together in end-to-end relation with removable modular antenna assembly carried by the reduced outer diameter end portion of the first tubular member
65
Finish
66

FIG. 7

REMOVABLE MODULAR ANTENNA ASSEMBLY FOR DOWNHOLE APPLICATIONS

TECHNICAL FIELD

This disclosure relates generally to antennas, such as those used in the well-logging applications, and related systems and methods.

BACKGROUND

Resistivity logging tools are used to measure the resistivities of earth formations surrounding a borehole, such as in a hydrocarbon (e.g., oil, natural gas, etc.) well. One approach for performing resistivity measurements is by lowering a wireline-conveyed logging device into a wellbore after the wellbore is drilled. Another approach is to make such measurements while the well is being drilled, which is referred to as logging-while-drilling (LWD) or measurement-while-drilling (MWD). LWD or MWD techniques may allow corrective actions to be taken during the drilling processes if desired. For example, wellbore information if available in real time may be used to make adjustments to mud weights to prevent formation damage and to improve well stability. In addition, real time formation log data may be used to direct a drill bit to the desired direction (i.e., geosteering).

Generally speaking, there are two types of LWD tools for measuring formation resistivity, namely lateral tools and induction or propagation tools. Each of these tools relies on an electromagnetic (EM) measurement principle. A lateral tool may use one or more antennas or electrodes to inject low-frequency transverse magnetic fields into the formations to determine borehole and formation responses by measuring the current flow through the formations to the receivers. Lateral resistivity tools are generally responsive to azimuthal variations in formation resistivities around the borehole.

Propagation-type tools emit high-frequency electric fields into the formation to determine borehole and formation responses by measuring voltages induced in the receivers or by measuring difference responses between a pair of receivers or between the transmitter and the receiver. For example, for a propagation tool, incoming signal phases and amplitudes may be measured at each of several receivers with respect to the phases and amplitudes of the signals used to drive the transmitter. Induction-type transmitters generate magnetic fields that induce currents to flow in the formations. These currents generate secondary magnetic fields that are measured as induced voltages in receiver antennas disposed at a distance from the transmitter antenna.

SUMMARY

This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the scope of the claimed subject matter.

A wellbore apparatus is provided herein which may include first and second tubular members joined together in end-to-end relation, the first tubular member having a reduced outer diameter end portion. The wellbore apparatus may further include a removable modular antenna assembly including a cylindrical dielectric housing removably positioned on the reduced outer diameter end portion of the first tubular member, at least one antenna coil carried by the cylindrical dielectric housing, and a first electrical connector coupled to the at least one antenna coil. The wellbore apparatus may also include resistivity processing circuitry coupled to the first electrical connector to determine an electrical resistivity of a wellbore based upon the at least one antenna coil.

A related method for making a wellbore apparatus may include providing first and second tubular members to be joined together in end-to-end relation, with the first tubular member including a reduced outer diameter end portion, and removably positioning a cylindrical dielectric housing of a removable modular antenna assembly on the reduced outer diameter end portion of the first tubular member. The removable modular antenna assembly may include at least one antenna coil carried by the cylindrical dielectric housing, and a first electrical connector coupled to the at least one antenna coil. The method may also include coupling the first electrical connector to resistivity processing circuitry, and joining the first and second tubular members together in end-to-end relation with the removable modular antenna assembly carried by the reduced outer diameter end portion of the first tubular member.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram of an LWD/MWD system including removable modular antenna assemblies in accordance with an example embodiment.

FIG. **2** is a schematic cross-sectional diagram of a removable modular antenna assembly and associated tubular members of FIG. **1** in accordance with a first example embodiment.

FIG. **3** is a schematic cross-sectional diagram of a portion of the removable modular antenna assembly and associated tubular member of FIG. **2** showing further details of the electrical connectors thereof.

FIG. **4** is a schematic cross-sectional diagram of an embodiment of a removable modular antenna assembly and associated tubular member.

FIG. **5** is a schematic cross-sectional diagram of another embodiment of a removable modular antenna assembly and associated tubular member.

FIG. **6** is a schematic cross-sectional diagram of still another embodiment of a removable modular antenna assembly and associated tubular members.

FIG. **7** is a flow diagram illustrating method aspects associated with the system of FIG. **1**.

DETAILED DESCRIPTION

The present description is made with reference to the accompanying drawings, in which example embodiments are shown. However, many different embodiments may be used, and thus the description should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete. Like numbers refer to like elements throughout, and prime notation is used to indicate similar elements in different embodiments.

Referring initially to FIG. **1**, a logging-while-drilling (LWD) or measurement-while-drilling (MWD) system **30** is first described. A drill string **31** is suspended within a borehole **32** with a drill bit **33** attached at the lower end. The drill string **31** and attached drill bit **33** are rotated by a rotating table **34** while being lowered into the well, although other approaches such as a top drive may be used instead of the rotating table. This causes the drill bit **33** to penetrate the geological formation **35**. As the drill bit **33** penetrates the formation **35**, drilling fluid or "mud" is pumped down through a bore of the drill string **31** (which may be a central bore, offset bore, or annular bore, for example) to lubricate the drill bit **33** and to carry cuttings from the bottom of the hole to the surface via the borehole **32** and mud flow line **36**. Located behind drill bit **33** in the drill string **31** (i.e., vertically above the drill bit in FIG. **1**) are sections of LWD drill collar tubulars **37**, which may include a plurality of removable modular antenna assemblies **40** positioned between adjacent drill collar tubulars. The removable modular antenna assemblies **40** are used to measure the resistivity of the formation **32** as it is penetrated by the drill bit **33**. It should be noted that the removable modular antenna assemblies **40**, which will be discussed further below, may also be used in a wireline measurement system as well.

Referring more particularly to FIGS. **2** and **3**, a first embodiment of the removable modular antenna assembly **40** is now described. By way of background, an antenna for downhole use may includes one or more coils enclosed in an insulator material. The insulator material may be built in a recess of a downhole tubular (e.g. tool housing, collar, etc.), and permanently installed on the tool. However, the removable modular antenna assembly **40** illustratively includes a cylindrical dielectric housing **41** that is removably positioned on a reduced outer diameter end portion **42** of a first tubular member **43**. The first tubular member **43** may then be joined together in an end-to-end relation with a second tubular member **44**, with the removable modular antenna assembly **40** therebetween, as seen in FIG. **2**. The second tubular member **44** also illustratively includes a reduced outer diameter end portion **45** in the present example, although in other embodiments it does not have to have a reduced outer diameter portion.

The removable modular antenna assembly **40** further illustratively includes one or more antenna coils **46** carried by the cylindrical dielectric housing **41**, and a first electrical connector **47** coupled to the antenna coil(s). A second electrical connector **48** is carried by the first tubular member **43** and coupled with resistivity processing circuitry **49**. The second electrical connector **48** mates with the first electrical connector **47** to thereby provide an electrical connection between the antenna coil **46** and the resistivity processing circuitry **49**, which determines an electrical resistivity of a wellbore based upon the antenna coil. The resistivity processing circuitry illustratively includes a controller and a transmitter and/or receiver **51** coupled thereto. As noted above, multiple antenna assemblies **40** may be spaced apart along the drill string **31** to transmit and receive signals to and from the geological formation **35**. As such, the controller **50** may interface with multiple transmitters and receivers for respective antenna assemblies **40**. Transmitters and receivers may also be coupled to multiple antenna assemblies **40** (i.e., shared), and a given antenna assembly may be used to alternate between transmitting and receiving in some embodiments.

The controller **50** may be carried on the drill string **31** in the tool section behind the drill bit **33** in an electronic chassis. The controller **50** may collect resistivity measurement data and store it for later retrieval (such as when the drill string **31** is removed from the borehole **32**), or it may communicate the resistivity measurement data up to a well logging control center outside of the well via telemetry or a wired connection. The controller **50** may first process the measured values to make resistivity determinations, or it may collect raw measurement data for later processing.

In the example illustrated in FIGS. **2** and **3**, when the cylindrical dielectric housing **41** slides over the reduced outer diameter end portion **42** of the first tubular member **43**, the first electrical connector **47**, which is a male connector in the illustrated example, plugs into the second electrical connector **48**, which is a female connector in this example. It should be noted, however, that the first electrical connector **47** may be a female connector and the second electrical connector **48** may be a male connector in some embodiments, or other suitable types of connector arrangements may be used.

In the illustrated example, the reduced outer diameter end portion **42** of the first tubular member **43** defines a shoulder **52** with adjacent portions of the first tubular member, and the second electrical connector **48** is carried by the shoulder as shown. An electrical connection is achieved upon sliding the antenna assembly **40** into place on the reduced outer diameter portion **42**, which will engage the first electrical connector **47** into the second electrical connector **48**. In the present example, the reduced outer diameter end portion **45** of the second tubular member **44** may then be inserted in the cylindrical dielectric housing **41** and coupled with the reduced outer diameter end portion **42** of the first tubular member **43** (e.g., they may be threadably coupled together). However, in other embodiments where the second tubular member **44** does not have the reduced outer diameter portion **45**, the antenna assembly will slide onto the first tubular member **43**, and the second tubular member is coupled to the reduced diameter portion **42** of the first tubular member. For example, the inner surface of the second tubular member **44** may have threads for engaging corresponding threads on the reduced outer diameter portion **42** of the first tubular member **43**, or they may be coupled by other suitable connectors.

It should also be noted that more than one antenna assembly **40** may be positioned between the first tubular member **43** and the second tubular member **44** in the present embodiment, as well as the other embodiments discussed below. That is, one or more antenna assemblies **40** may be positioned on the reduced diameter portion **42** of the first tubular member **43**, and if the second tubular member **44** also includes the reduced outer diameter portion **45**, then one or more antenna assemblies may be positioned there as well.

In the present example, the first electrical connector **47** comprises a body portion **53** that is integrally formed or molded with the dielectric housing **41** (although it may be separately installed in some embodiments) and includes at least one electrode **54** carried by the body portion. Furthermore, a sealing ring(s) **55** is also associated with the removable modular antenna assembly. In the present example, the sealing ring **55** is carried by the body portion **54** to seal out water, mud, dirt, or other materials that could compromise the electrical connection to the resistivity processing circuitry **49**. In some embodiments, a set screw or other locking device may also be used to securely couple the first and second connectors **47**, **48** together, if desired.

A related method for making a wellbore apparatus is now described with reference to the flow diagram **60** of FIG. **7**. Beginning at Block **61**, the method illustratively includes providing the first and second tubular members **43**, **44** to be joined together in end-to-end relation (Block **62**). The method further includes removably positioning the cylindrical dielectric housing **41** of the removable modular antenna assembly **40** on the reduced outer diameter end portion **42** of the first tubular member, at Block **63**. Furthermore, the first electrical connector **47** is coupled to the resistivity processing circuitry **49** (e.g., via the second electrical connector **48**), at Block **64**, and the first and second tubular members **43**, **44** are joined together in end-to-end relation with the removable modular antenna assembly **40** carried by the reduced outer diameter end portion **42** of the first tubular member, at Block **65**, which concludes the method illustrated in FIG. **6** (Block **66**).

Turning now to FIG. **4**, in accordance with another example embodiment the first tubular member **43'** has a connector-receiving recess in an outer portion thereof adjacent the reduced outer diameter end portion **42'**, and the second electrical connector **48'** is carried by the connector-receiving recess. Moreover, the first electrical connector **47'** comprises a pigtail electrical connector to couple to the corresponding second electrical connector **48'** in the connector-receiving recess on the outer portion of the first tubular member **43'**. Here again, a seal or sealing ring may optionally be used to help prevent contaminants from compromising the electrical connection between the first electrical connector **47'** and the second electrical connector **48'**.

In accordance with another example embodiment shown in FIG. **5**, the reduced outer diameter end portion **42"** of the first tubular member **43"** comprises a dielectric layer or region **56"** adjacent the removable modular antenna assembly **40"**. More particularly, the dielectric layer is positioned beneath where the cylindrical dielectric body **41"** is positioned when the first electrical connector **47"** is plugged into the second electrical connector **48"**. This embodiment allows the first tubular member **43"** to have a larger outer diameter along the reduced diameter portion **42"** while providing desired depth for the electrical insulator under the antenna coil **46"**. In this embodiment, the cylindrical dielectric housing **41"** is again slidably received on the reduced outer diameter end portion **42"** of the first tubular member **43"**, as described above.

Turning now to FIG. **6**, in still another example embodiment the second tubular member **44'''** includes the reduced outer diameter end portion **45'''**, as noted above, and the removable modular antenna assembly **40'''** further includes a coupler body **57'''** carrying the cylindrical dielectric housing **41'''** and threadably coupling the reduced outer diameter end portions **42'''**, **45'''** of the first and second tubular members **43'''**, **44'''** together, as shown. Here again, sealing rings **58'''** may be included to promote a seal between the first and second tubular members **43'''**, **44'''** and the coupler body **57'''**, if desired.

It will be appreciated that the above-described removable modular antenna assemblies may be installed and uninstalled on a downhole tubular (such as a housing or collar), removed, or replaced as desired. This may allow antennas to be readily replaced in the field when worn or damaged, rather than having to remove large drill collars or other tubular sections and send them offsite for service or re-fitting of permanent embedded antennas, for example. Additionally, the removable antenna assemblies allow pressure balancing, thus reducing size variation with pressure. In some embodiments, the antenna coil **46** may be mounted on a ceramic or polymer core, and then molded in a fluid resistant polymer or elastomer (e.g., rubber). Example dielectric material may include PEEK, SPS or other thermoplastic or thermoset, for example.

Many modifications and other embodiments will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that various modifications and embodiments are intended to be included within the scope of the appended claims.

That which is claimed is:

1. A wellbore apparatus comprising:

first and second tubular members, each of the first and the second tubular members comprising an end portion having a first outer diameter;

a removable modular antenna assembly comprising,

a hollow cylindrical dielectric housing comprising an inner wall and an outer wall, the inner wall comprising an inner wall diameter larger than the first outer diameter,

at least one antenna coil carried by said hollow cylindrical dielectric housing;

a dielectric material disposed around the at least one antenna coil and carried by said hollow cylindrical dielectric housing between the inner wall and the outer wall, wherein during operations of the wellbore apparatus the outer wall of the hollow cylindrical dielectric housing is exposed in a wellbore; and

a first electrical connector coupled to said at least one antenna coil; and

resistivity processing circuitry coupled to said first electrical connector to determine an electrical resistivity of a wellbore based upon said at least one antenna coil, wherein the first tubular member is removably inserted into the hollow cylindrical dielectric housing via a first opening of the hollow cylindrical dielectric housing and wherein the first tubular member is coupled to the second tubular member so that the first and the second tubular members are on a same axis and the end portions face each other.

2. The wellbore apparatus of claim **1** further comprising a second electrical connector coupled to said resistivity processing circuitry, carried by said first tubular member, and mating with said first electrical connector.

3. The wellbore apparatus of claim **2** wherein the end portion of said first tubular member defines a shoulder with adjacent portions of said first tubular member; and wherein said second electrical connector is carried by the shoulder.

4. The wellbore apparatus of claim **2** wherein said first tubular member has a connector-receiving recess in an outer portion thereof adjacent the end portion; and wherein said second electrical connector is carried by the connector-receiving recess.

5. The wellbore apparatus of claim **1** wherein said first connector comprises a body portion integrally formed with said dielectric housing and at least one electrode carried by said body portion.

6. The wellbore apparatus of claim **1** comprising a second removable modular antenna assembly, wherein the second tubular member is removably inserted into a second hollow cylindrical dielectric housing of the second removable modular antenna assembly via a second opening of the second hollow cylindrical dielectric housing.

7. The wellbore apparatus of claim **1** wherein the diameter end portion of said first tubular member comprises a dielectric layer adjacent said removable modular antenna assembly.

8. The wellbore apparatus of claim **1** wherein said removable modular antenna assembly further comprises a coupler body carrying said cylindrical dielectric housing and threadably coupling the end portions of said first and second tubular members together.

9. The wellbore apparatus of claim **1** wherein said dielectric housing is slidably received on end portion of said first tubular member.

10. The wellbore apparatus of claim **1** further comprising at least one sealing ring associated with said removable modular antenna assembly.

11. The wellbore apparatus of claim **1** wherein said resistivity processing circuitry comprises a controller and at least one of a transmitter and receiver coupled thereto.

12. The wellbore drilling apparatus of claim **1** wherein said first electrical connector comprises a pigtail electrical connector.

13. A method for making a wellbore apparatus comprising:

providing first and second tubular members to be joined together, with the first tubular member comprising a first end portion having a first outer diameter;

removably positioning a hollow cylindrical dielectric housing of a removable modular antenna assembly on the first end portion of the first tubular member, the removable modular antenna assembly comprising at least one antenna coil carried by the hollow cylindrical dielectric housing, and a first electrical connector coupled to the at least one antenna coil, the hollow cylindrical dielectric housing comprising an inner wall and an outer wall, the inner wall comprising an inner wall diameter larger than the first outer diameter;

disposing a dielectric material around the at least one antenna coil and between the inner wall and the outer wall of the hollow cylindrical dielectric housing, wherein during drill operations of the wellbore apparatus the outer wall of the hollow cylindrical dielectric housing is exposed in a wellbore;

coupling the first electrical connector to resistivity processing circuitry; and

joining the first and second tubular members together with the removable modular antenna assembly carried by the first end portion of the first tubular member, wherein the first tubular member is removably inserted into the hollow cylindrical dielectric housing via a first opening of the hollow cylindrical dielectric housing and wherein the first tubular member is coupled to the second tubular member so that the first and the second tubular members are on a same axis and the first end portion faces a second end portion of the second tubular member, wherein the second end portion comprises the first outer diameter.

14. The method of claim 13 wherein coupling comprises coupling the first electrical connector to resistivity processing circuitry via a second electrical connector coupled carried by the first tubular member and mating with the first electrical connector.

15. The method of claim 14 wherein the first end portion of the first tubular member defines a shoulder with adjacent portions of the first tubular member; and wherein the second electrical connector is carried by the shoulder.

16. The method of claim 14 wherein the first tubular member has a connector-receiving recess in an outer portion thereof adjacent the first end portion; and wherein the second electrical connector is carried by the connector-receiving recess.

17. The method of claim 13 wherein the first connector comprises a body portion integrally formed with the dielectric housing and at least one electrode carried by the body portion.

18. The method of claim 13 wherein the first electrical connector comprises a pigtail electrical connector.

19. The method of claim 13 wherein the removable modular antenna assembly further comprises a coupler body carrying the hollow cylindrical dielectric housing; and wherein joining comprises threadably coupling the first end portion and second end portion of the first and second tubular members together with the coupler body.

20. The method of claim 13 wherein joining comprises sliding the dielectric housing on the reduced outer diameter end portion of the first tubular member.

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